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Effects of Voltage and Wire Feed Speed on Weld Fume Characteristics

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Welding generates high concentrations of ultrafine particles, which research suggests may be more toxic than larger particles. Fume characteristics were measured in a controlled apparatus as a function of voltage level and wire feed speed. Particles were sampled close to the welding process on mixed cellulose ester membrane filters and analyzed for iron, manganese, and total particulate matter at an accredited industrial hygiene laboratory. An ultrafine condensation particle counter measured the particle number concentration, and an optical particle counter measured the particle size distribution. Submicrometer particle number concentrations and iron, manganese, and total particle mass concentrations all depended on voltage levels but not on wire feed speed at a constant voltage. Ultrafine particle concentrations were more than three times greater at 23.5 V than at 16 V. Particles 0.5–0.7 μm in diameter counted by the optical particle counter increased from 9800 particles/cm^3 at 16 V to 82,800 particles/cm^3 at 23.5 V. Manganese concentration was 1.7 mg/m^3 at 16 V vs. 6.4 mg/m^3 at 23.5 V. The data suggest that welders should use lower voltage levels whenever possible.

Keywords iron, manganese, particles, voltage, welding, wire feed speed

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BACKGROUND

Gas Metal Arc Welding

In 2004, about 429,000 U.S. workers held jobs that included welding among their duties.(1) There are more than 80 welding processes, one of the most common being gas metal arc welding (GMAW).(2) In arc welding, a power supply generates an electric arc between an electrode and a work piece to melt metals where the weld is needed. GMAW, which can be performed on steels, aluminum, and other metals, uses a consumable metal wire electrode that becomes part of the weld. Electrodes of many compositions are commercially available. GMAW also requires an inert shielding gas, often carbon dioxide, argon, helium, or mixtures of these and other gases to prevent reactions with atmospheric oxygen and nitrogen that can harm the properties of the weld as it forms.(3)

The average breathing zone concentration of fumes generated during GMAW is regularly between 1 and 5 mg/m^3.(4) Research suggests that these fumes are predominantly composed of submicrometer particles,(5,6) which appear to be more toxic than an equal mass of larger particles with similar composition.(7) These particles penetrate deep into the lungs and deposit in the alveolar region where even nuisance dusts can be highly toxic.(7)

Welding fumes are particles derived from three main sources: (1) droplets of molten wire from the consumable electrode; (2) the weld pool of molten electrode and base metal that will cool to form the hardened weld; and (3) spatter, droplets of weld metal that are expelled from the welding operation and attach to the base metal.(8) The fumes are formed through four processes: (1) physical ejection of particles, (2) oxidation-enhanced evaporation, (3) evaporation followed by condensation, and (4) contribution of spatter to fume formation. Physical ejection of particles due to bubble bursting or turbulence and oxidation-enhanced vaporization do not contribute a significant proportion to the total fume.(9)

During the welding process, droplets of molten wire electrode, pools of molten electrode and base metal, and droplets spattering from the pools are potential sources for evaporative emissions that condense in the surrounding air to form particles. It has been hypothesized that evaporation of metals from these droplets and pools contributes greatly to the welding fume.(9) This is supported by the finding that relatively volatile metals such as manganese are more prevalent on a mass percentage basis in the fume particles than in the wire and base metal.(9) An unstable arc and a turbulent weld pool, which create spatter, also contribute significantly to the fume. Spatter increases the surface area of molten metal and ejects it to the more oxidizing general atmosphere.(9)

Metal Transfer Types

The metal transfer type, the mechanism by which the molten metal from the electrode is applied to the base metal, is a critical parameter for welding in manufacturing. It determines the

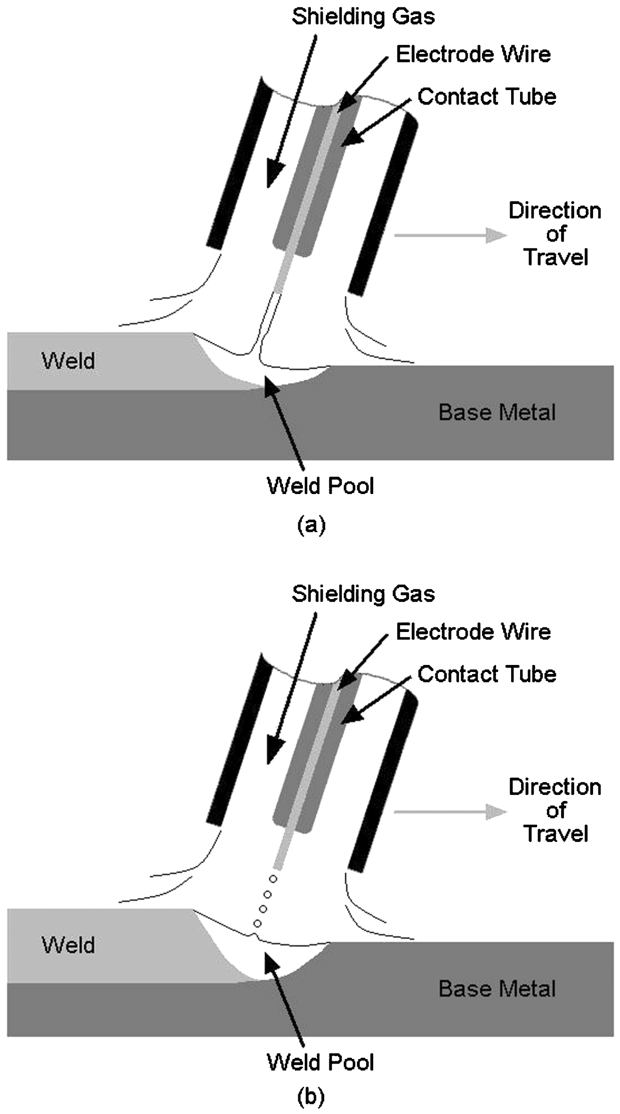

FIGURE 1. Types of metal transfer: (a) short circuit transfer, (b) spray arc transfer

penetration, strength, and position of the weld. In GMAW, there are four different metal transfer processes: (1) short circuit, (2) globular, (3) spray, and (4) pulse.

Short circuit transfer happens at lower voltage levels and wire feed speeds, and with intermittent short-circuiting of the arc (Figure 1a). The melting wire electrode extends until it makes contact with the base metal, short-circuiting the arc, which creates a spike in current that causes the wire tip to melt completely and separate from the rest of the electrode in globular form.(10) After the arc is re-established, the process repeats itself. Because the arc is short circuited, the heat output is much lower than spray transfer, which has a constant arc. Short circuit transfer is suitable for welding thinner metals, multipass welding on thick substrates, and when out of position because the weld pool is less likely to drip. However, its penetration is not as deep as spray transfer.

Spray transfer occurs at higher voltage levels and wire feed speeds, and has a constant arc (Figure 1b). Due to the increased voltage, the droplets are projected across the arc at a high rate. This causes the droplets to become smaller, creating a fine spray. Due to the constant arc, the heat output and the rate of deposition are higher, and the penetration is deeper. However, spray transfer at a constant current is more difficult to use than short circuit transfer in vertical and overhead positions because the heat and size of the weld pool make it more likely to drip.(3) The droplets formed during spray transfer are sensitive to the type of shield gas used. Argon shield gas is used to eliminate as much oxygen exposure as possible so the droplets transfer smoothly to the work. Using carbon dioxide to shield the arc is less smooth and produces more spatter.(10)

Globular transfer shares many characteristics with short circuit transfer but happens at a slightly higher voltage level that causes the melting wire to separate from the electrode before short circuiting occurs.(3) Pulse transfer is a variation of spray transfer in which a pulsed current sufficient to initiate a short burst of spray transfer is superimposed on a constant background current at regular intervals (60–120 pulses/s). Although a specially designed power supply is required for pulse transfer, this mechanism retains many of the desirable properties of spray transfer, such as depth of weld penetration, while allowing easier out-of-position welding.(3)

Each of the four metal transfer types has distinct characteristics. As the voltage level increases, so does the penetration of the weld.The surface area of molten wire also increases with voltage and temperature. It has been shown that mass concentrations of welding fumes also increase with voltage.(11)

GMAW Fumes

Welding is an obvious source of ultrafine particles because of the metal vaporization caused by the intense heat and molten surface area. The vaporized molecules condense to create ultrafine particles with high surface area per unit volume.(6) GMAW process parameters affect the fume formation and composition. Increases in voltage and oxidizing gas increase the amount of fume generated by a process.(11) Zimmer et al.(6) noted similar particle number concentrations for globular transfer at 20.5 V and spray transfer at 30.5 V when measuring particles with diameters between 16.5 and 562 nm and using the same welding wire feed speed for each process. However, they found an order of magnitude higher particle number concentration with spray transfer for particles 16.5 nm and smaller in diameter. Increased voltage was correlated to higher chromium VI levels in fumes when chromium was present in the welding wire.(12) Research has shown that the welding wire is the main contributor to the fume composition.(11)

Health Effects

Although ultrafine particles outnumber larger particles in welding fumes, their low mass means they are not accounted for readily by gravimetric measurements. In addition, recent research generally indicates that the size of the particle is a critical factor in its toxicity.(7,13) Systematic studies of the toxicity of ultrafine particles have only recently begun.(14)

Ultrafine particles pose a health risk to the lungs and other organs. Their increased surface area makes them more chemically reactive and increases lung inflammation as a result.(7,15) Furthermore, smaller particles are able to penetrate far deeper into the lungs. Whereas large particles may become entrapped in the mucus of the upper airways, small particles are able to travel to the alveoli. Once in the alveoli, many ultrafine particles are able to cross over into the bloodstream via the epithelial barrier.(13)

Inhalation of welding fumes is associated with metal fume fever, siderosis, and lung cancer.(16) Metal fume fever is an acute respiratory illness associated with overexposure to metals common to galvanized steel welding (zinc, copper, cadmium). Long-term exposure to iron oxide can lead to siderosis, a form of pneumoconiosis that occurs when iron oxide particles accumulate in the alveolar macrophages. Although mild steel welding does not appear to be a risk factor for developing lung cancer, stainless steel welding, which creates fumes with chromium and nickel, is a risk factor for developing lung cancer.

Manganese, a common constituent of welding wire, has been clearly shown to be a neurotoxicant when inhaled at high levels. The clinical syndrome of manganese poisoning features behavioral changes, parkinsonian symptoms, and dystonia with severe gait disturbances.(17) Roels et al.(18) found that workers exposed to manganese were more likely to have a cough and express sputum, suffer from acute bronchitis, exhibit less hand steadiness, and perform significantly worse on simple reaction time, short-term memory capacity, and hand-eye coordination tests than unexposed workers. Studies of small groups of welders have indicated that welding on the job is associated with a higher incidence of adverse neurological and neuropsychological health effects.(19–22) In three of these studies, the effects were associated with elevated exposures to airborne manganese.(19,20,22) In a screening of 1423 welders from Alabama, Racette et al.(23) found higher levels of parkinsonism relative to a comparison population of male residents in Missouri.

Nonetheless, manganese oxides in welding fumes have not been conclusively associated with neurological disease.(16) Some studies have found little or no indication of an association. For example, Fryzek et al.(24) found that the rates and age at onset of neurodegenerative disease for workers, including welders, engaged in metal manufacturing in Denmark were comparable to the general population. The potential association between manganese exposure and neurological effects in welders remains a contentious issue that awaits further research before it can be resolved.

The Occupational Safety and Health Administration (OSHA) does not currently regulate weld fume exposure directly. Relevant standards include particles not otherwise regulated and individual metals found in the fumes.

Similar Exposure Groups

Similar exposure groups are used to better categorize employee exposures to workplace hazards. Sample data can be extrapolated to make estimates for groups of employees with similar exposures without sampling every individual. Prior to establishing similar exposure groups, an industrial hygienist needs to understand the exposure.(25) One concern is that worker populations with too broad a range of exposures may not be sampled sufficiently to determine appropriate exposure controls. For welding operations, the literature clearly shows that airborne particle concentrations vary because the welding parameters affect the fume generation.(6,11,12) Identifying parameters that are key to determining exposure levels would help in defining similar exposure groups among welders.

Research Objectives

Welding creates particles that can cause adverse health effects. The objective of this study was to determine if the welding process parameters could be adjusted to reduce mass and number concentrations of particles and constituent metals to which workers are exposed. This work also sought to better define exposure as a function of key welding parameters, which could be useful when establishing similar exposure groups for the application of exposure controls.

METHODS

Weld Apparatus

A weld apparatus was constructed for consistent welds. Key elements included a wire feed welder, a horizontal positioning table, and a rotating positioner. The wire feed welder was a Millermatic 251 (Miller Electric Manufacturing Co., Appleton, Wisc.).

A reproducible GMAW operation was initiated for one of the combinations of voltage and wire feed speed listed in Table I using 75% CO_2 and 25% Ar shield gas. A standard solid wire electrode,(26) class ER70S-6 (Washington Alloy Co., Rancho Cucamonga, Calif.), was used. The wire constituents, percent by weight, were: Mn, 1.70%; C, 0.10%; Si, 1.00%; P, 0.01%; S, 0.02%; and Fe, 97.18%. Welding was done on mild steel cylinders 0.48 cm thick, 15.2 cm in diameter, and 30.5 cm long. The cylinders rotated at 47.8 cm/min on the rotating positioner and were indexed about 2 cm manually between welds using the horizontal positioner so that a new section of the cylinder was welded on. The rotating positioner kept the linear axes of the cylinders parallel to the ground.The apparatus produced a consistent weld around the tube.

Each test consisted of on and off periods. The weld would be on for 1 min and then off for 15 sec during which the cylinders were indexed horizontally. Measurements were averaged over the course of the test; tests ranged from 4 to 25 min. The time range depended on the heat buildup in the base metal. At higher voltage levels, the weld would burn through the base metal after approximately 5 min.

TABLE I. Test Conditions

Voltage	−0.254 m/min from Recommended WFS	WFS Recommended by Manufacturer (m/min)	+ 0.254 m/min from Recommended WFS
16	3.94	4.19	4.45
18	6.86	7.11	7.36
21.5	10.54	10.80	11.05
23.5	11.81	12.07	12.32

Note: WFS = Wire feed speed

Sampling Instruments and Materials

Measurements of fume characteristics were made at fixed sampling positions relative to the welding gun. Inlets for an optical particle counter (HHPC-6, Hach Ultra Analytics, Grants Pass, Ore.) and an ultrafine condensation particle counter (P-Trak, TSI, Shoreview, Minn.) were located 40.6 cm horizontally from the weld position, while a 37-mm closed-face filter cassette was 17.8 cm above the weld position. The zero levels of the optical particle counter (OPC) and ultrafine condensation particle counter (UCPC) were confirmed before each test. The sampling pump for the filter cassettes was calibrated to 2.0–2.1 L/min before daily measurements. The manufacturers of the OPC and UCPC acknowledge the potential for particle losses during sampling when extendable probes for the samplers are used. Therefore, the probes were not used in this study.

The OPC was capable of simultaneously counting and sizing particles into six size bins ranging from 0.3 μm to greater than 5.0 μm. According to the manufacturer, the OPC has 50% counting efficiency for particles with a diameter of 0.3 μm and 100% efficiency for particles with diameters larger than 0.45 μm. The UCPC's manufacturer stated that the instrument was capable of counting ultrafine particles from 0.02 μm to greater than 1.0 μm.

The 37-mm cassettes holding mixed cellulose ester (MCE) filters were attached to a personal sampling pump with PVC tubing. The sampling procedure was based on NIOSH Method 0500(27) for total particulate mass.The filters were analyzed for iron, manganese, and total particulate mass at an AIHA accredited lab.

The duct entry for a welding fume extractor (Air Cleaning Systems Inc., Chardon, Ohio) was positioned 42 cm above the weld. This distance was selected because the device removed most of the particles observed rising from the welding operation without disrupting the shield gas. Experiments were performed in a room with poor ventilation; thus, the welding fume extractor was used to lower the particle exposure for the researcher and reduce fume concentrations between welds.

Test Conditions and Matrix

Particle concentrations were measured for three wire feed speeds at each of four voltage levels as shown in Table I. Conditions for voltage settings and wire feed speed were taken from recommendations from the manufacturer of the weld machine used during tests. The welds were not strength tested to validate the voltage levels.

Voltages of 16 and 18 V represented short circuit arc metal transfer during welding, whereas 21.5 and 23.5 V represented spray arc metal transfer. The same wire feed speeds could not be used for every voltage level. Every voltage level has an ideal wire feed speed for a stable weld. Wire feed speed was tested at the optimal level and at +0.254 and −0.254 m/min (+10 and −10 inches per minute) from the ideal setting. Three tests were run for each combination of voltage and wire feed speed.

Analysis Procedures

The cassette samples were analyzed using standard analytical procedures. The total particle mass was evaluated gravimetrically according to NIOSH Method 0500.(27) The iron and manganese concentrations were determined using inductively coupled plasma with atomic emission spectroscopy (ICP-AES) according to NIOSH Method 7300.(28)

Data from all three instruments were evaluated statistically by analysis of variance using PROC GLM in SAS software (SAS Inc., Cary, N.C.) to determine the effects of voltage, wire feed speed relative to the optimal setting at each voltage, and the interaction of voltage and relative wire feed speed on fume characteristics. The response variables were: UCPC particle number concentration; OPC particle number concentrations in six particle diameter intervals; total particulate, iron, and manganese mass concentrations; and ratios of iron and manganese mass concentration to total particle mass concentration.

As Table I shows, the absolute wire feed speed recommended by the welding machine manufacturer varied with voltage. To determine if any differences in response variables as a function of voltage were due strictly to the quantity of wire consumed at each voltage, the UCPC particle number concentration; the OPC particle number concentrations in the six particle diameter intervals; and the total particulate, iron, and manganese mass concentrations were divided by the wire feed speed for each test. The resulting normalized variables were each evaluated statistically using analysis of variance in SAS to determine the effects of voltage on them. These normalized variables were also evaluated in an analysis of variance against transfer type, with short circuit transfer representing tests at 16 and 18 V and spray transfer representing tests at 21.5 and 23.5 V.

TABLE II. P-values for Influence of Voltage, Wire Feed Speed (WFS), and Their Interaction on Response Variables

Response Variable	Voltage p-value	WFS p-value	Interaction p-value
UCPC number concentration	<0.0001*	0.37	0.098
OPC 0.3–0.5 μm number concentration	<0.0001*	0.20	0.37
OPC 0.5–0.7 μm number concentration	<0.0001*	0.069	0.40
OPC 0.7–1.0 μm number concentration	0.0002*	0.58	0.95
OPC 1.0–2.0 μm number concentration	<0.0001*	0.21	0.69
OPC 2.0–5.0 μm number concentration	<0.0001*	0.16	0.56
OPC >5.0 μm number concentration	0.66	0.42	0.38
Total particle mass concentration	0.0005*	0.63	0.26
Iron mass concentration	0.0001*	0.46	0.17
Manganese mass concentration	0.0005*	0.27	0.13
Iron mass/total particle mass	0.62	0.45	0.65
Manganese mass/total particle mass	0.017*	0.33	0.057

*p-values considered significant at a level of $p < 0.05$.

RESULTS

Effects of Voltage on Non-Normalized Response Variables

The voltage level had a significant effect ($p < 0.05$) on all response variables not normalized for wire feed speed except for the concentration of particles with diameters greater than 5.0 μm measured by the OPC and the ratio of iron mass to total particle mass on the filters. Table II presents p-values for the statistical analysis of the effects of voltage on each of the response variables. Figure 2 shows the effect of voltage on particle number concentrations. For the UCPC data and for OPC data for particles 5.0 μm in diameter and smaller particle number concentration increased with increasing voltage.

Figure 3 shows the effect of voltage on total particle, iron, and manganese mass concentrations. These concentrations generally increased from 16 to 21.5 V but were about the same for 21.5 and 23.5 V. Figure 4 illustrates the influence of voltage on the ratios of iron and manganese mass to total particle mass. The iron-to-total particle mass ratio remained constant with voltage, but the manganese-to-total particle mass ratio decreased slightly as voltage increased. Manganese made up about 10% of the weld fume even though it was only 1.70% of the weld wire.

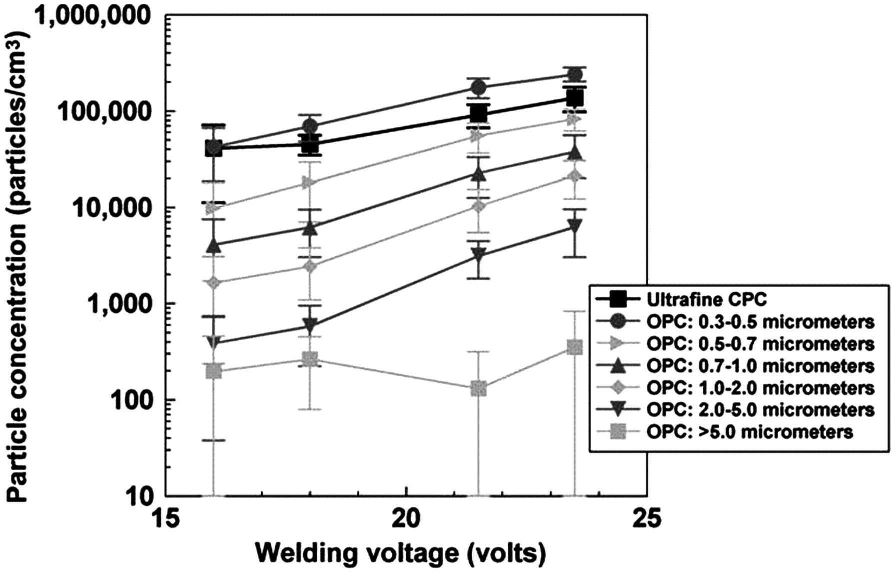

FIGURE 2. Particle number concentration as a function of welding voltage for particles measured by the ultrafine condensation particle counter (UCPC) and the six size channels on the optical particle counter (OPC). Data points are connected by straight lines. Error bars represent 95% confidence intervals around the mean for each condition.

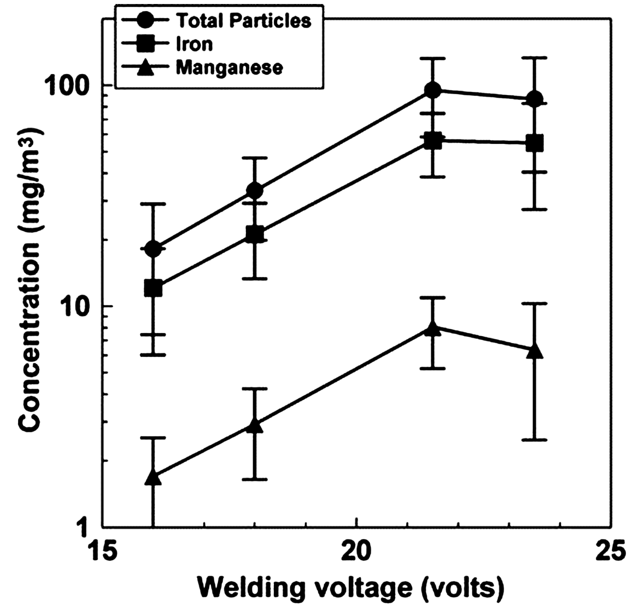

FIGURE 3. Total particle, iron, and manganese mass concentrations as a function of welding voltage. Data points are connected by straight lines. Error bars represent 95% confidence intervals around the mean for each condition.

Effects of Wire Feed Speed

Figure 5 illustrates the effects of wire feed speed, relative to the optimum for each voltage, on particle number concentrations. Figure 6 shows the influence of wire feed speed on total particle, iron, and manganese mass concentrations. Both figures indicate that differences in the wire feed speeds tested for an individual voltage level had little impact on particle number or mass concentration. Table II highlights that changes to wire feed speed at a particular voltage had no statistically significant effect on any of the response variables tested when $p < 0.05$ is considered significant.

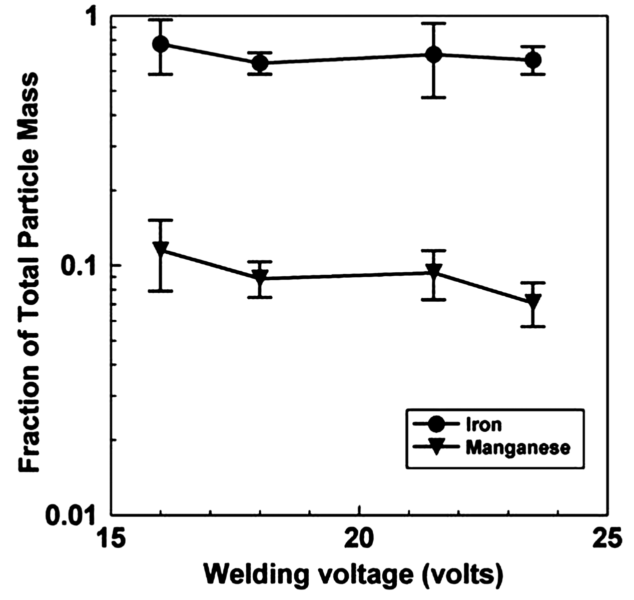

FIGURE 4. Fraction of iron and manganese in the total particle mass as a function of welding voltage. Data points are connected by straight lines. Error bars represent 95% confidence intervals around the mean for each condition.

Interaction Effects

As indicated by the p-values listed in Table II, the interaction of voltage and wire feed speed did not have a significant influence on any of the response variables if $p < 0.05$ is taken to be the indicator of statistical significance.

Effects of Voltage with Response Variables Normalized by Wire Feed Speed

Figure 7 illustrates the influence of voltage normalized by the absolute wire feed speed on particle number concentrations. Normalized particle concentration increased as voltage increased for particles 5.0 μm in diameter and smaller measured by the OPC. However, the influence of voltage is not as pronounced as it was in Figure 2 before normalization. For particles counted by the UCPC and particles greater than 5.0 μm in diameter counted by the OPC, no obvious relationship exists between normalized particle concentration and voltage.

Figure 8 shows the effect of voltage on total particle, iron, and manganese mass concentrations normalized by wire feed speed. The concentrations for 21.5 and 23.5 V, the spray transfer mode voltages, were generally higher than those for 16 and 18 V, the short circuit transfer voltages. However, the effect of voltage on normalized mass concentrations is not as pronounced as the influence of voltage on the concentrations in Figure 3 before they were normalized.

Table III presents p-values for the statistical analysis of the effects of voltage on each of the normalized response variables. Voltage was a significant influence, defined as $p < 0.05$, only for normalized OPC particle concentrations for particles 5.0 μm in diameter and smaller. Table III also shows the p-values for the separate analysis of the influence of transfer type on the normalized response variables. In addition to the OPC concentrations for particles 5.0 μm in diameter and smaller, the total particle, iron, and manganese concentrations are significant at $p < 0.05$ as a function of transfer type (short circuit vs. spray).

DISCUSSION

The results in Figures 2 and 3 and Table II indicate that the mass and number concentrations of welding-related particles are related to voltage. For all concentration response variables except OPC particles larger than 5.0 μm in diameter, the concentrations increased with increasing voltage. The concentrations for 23.5 V were significantly higher statistically than concentrations at 16 and 18 V for all of the response variables. Ultrafine, 0.3–0.5 μm, and 0.5–0.7 μm particle number concentrations and total particle and iron mass

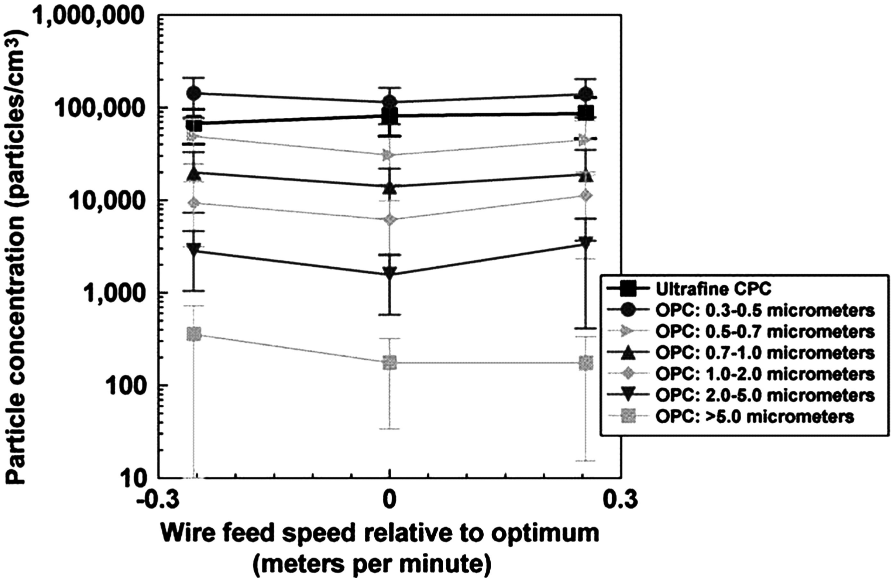

FIGURE 5. Particle number concentration as a function of wire feed speed for particles measured by the ultrafine condensation particle counter (UCPC) and the six size channels on the optical particle counter (OPC). Data points are connected by straight lines. Error bars represent 95% confidence intervals around the mean for each condition.

concentrations at 21.5 V were significantly higher statistically than the corresponding concentrations at 16 and 18 V.

As the voltage level increases, the type of metal transfer changes from short circuit to spray arc, which affects the heat of the weld, wire feed speed, and molten surface area. Short circuit transfer, achieved in this study at 16 and 18 V, does not create a constant arc. The electrode short circuits, frequently keeping the temperature lower. The lowered temperature could reduce the amount of metal vaporization and subsequent recondensation that occurs. Thus, less vaporization at lower voltage levels could account for part of the reduced particle concentrations. In addition, short circuit transfer has much less surface area available for vaporization than spray arc transfer at higher voltages. This could also contribute to the relatively lower particle concentrations during short circuit transfer.

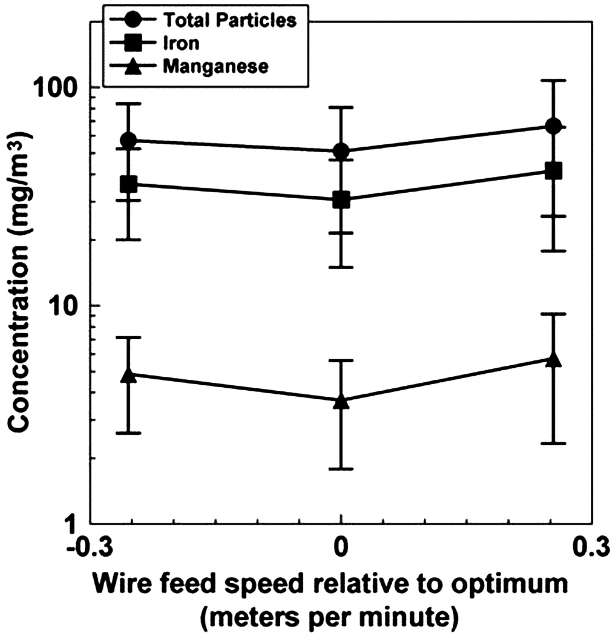

FIGURE 6. Total particle, iron, and manganese mass concentrations as a function of wire feed speed. Data points are connected by straight lines. Error bars represent 95% confidence intervals around the mean for each condition.

During spray arc transfer, which happened at higher voltage levels of 21.5 and 23.5 V, the wire showered down on the base metal. It created much more molten surface area for vaporization. The increased vaporization could account for the increased fume concentration. The constant current of spray transfer also created more heat output that could drive more vaporization from the spray transfer droplets. In combination with the increased area of the spray transfer droplets, the increased heat could speed up the volatilization of the metals, leading to relatively high particle concentrations after recondensation.

Because the experiment used a mixed carbon dioxide/argon shield gas instead of pure argon, the spray metal transfer was less smooth than it could have been. Particles were likely ejected from the shield gas to the ambient environment more easily than if pure argon had been used.(11) These particles contribute to fume levels in two ways: (1) they contribute directly to the levels of large particles, (2) and they create an additional opportunity for more vaporization and recondensation into small particles. The use of argon rather

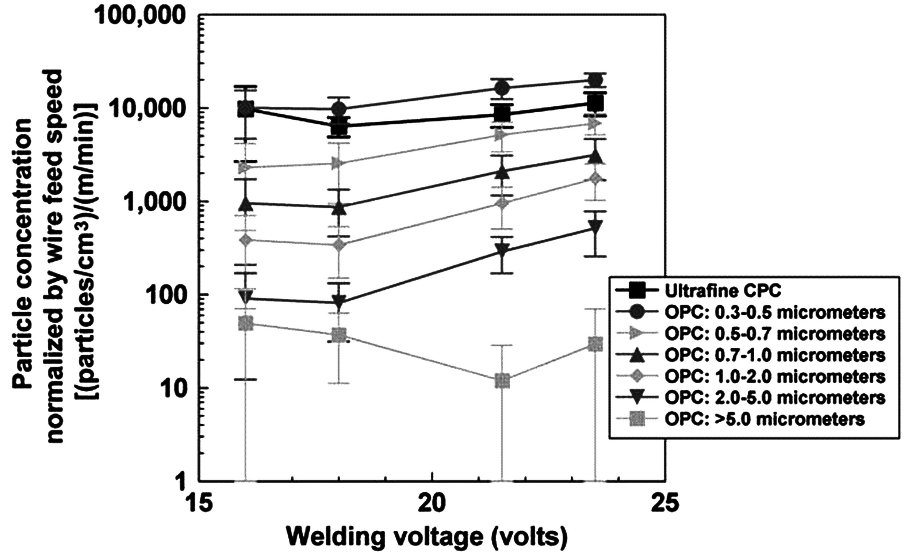

FIGURE 7. Particle number concentration normalized by wire feed speed plotted as a function of welding voltage for particles measured by the ultrafine condensation particle counter (UCPC) and the six size channels on the optical particle counter (OPC). Data points are connected by straight lines. Error bars represent 95% confidence intervals around the mean for each condition.

than the mix could potentially reduce the significance of the effects observed for voltage in this study.

Manganese has a substantially lower boiling point than iron.[29] Therefore, manganese will vaporize more easily than iron, leading to a higher presence on a percentage basis in welding fumes than in the original wire.The percentage of manganese in the particles on a mass basis was 7.1% for a voltage of 23.5 V, which was significantly lower than the 11.5% observed at 16 V. This suggests that the composition of the particles depends on the voltage level.

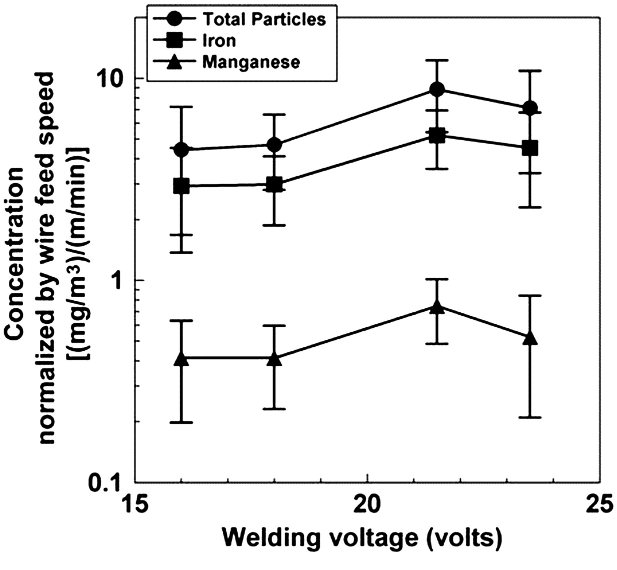

FIGURE 8. Total particle, iron, and manganese mass concentrations normalized by wire feed speed plotted as a function of welding voltage. Data points are connected by straight lines. Error bars represent 95% confidence intervals around the mean for each condition.

Over the ranges tested, Figures 5 and 6 and Table II show that wire feed speed relative to the optimum speed at each voltage level did not have a statistically significant effect on particle concentration or composition for any of the response variables. Not surprisingly, Table II also shows that the interaction of this relative wire feed speed and voltage did not significantly influence any of the response variables. If a broader range of wire feed speeds relative to the optimum were tested, however, some significant effects could emerge.

The analysis of wire feed speed relative to the optimum at each voltage level does not indicate whether changes in the optimum wire feed speed as a function of voltage contribute significantly to fume concentrations. Because absolute wire feed speed increased with increasing voltage, the two variables were confounded statistically in the study design. Nonetheless, when the absolute wire feed speed was used to normalize concentration data to account for the larger quantity of wire consumed at higher voltages, the influence of voltage on the response variables was reduced noticeably. This finding suggests that the higher particle concentrations at elevated voltages may be caused not only by the change from short circuit to spray transfer, but also by the increased use of wire during spray transfer.

The results in this paper are similar to findings from Gray and Hewitt,[11] who reported that fume generation increased as voltage levels increased. However, Zimmer et al.[6] did not observe particle concentration increases for particles between 16.5 and 562 nm as metal transfer changed from globular transfer at 20.5 V to spray transfer at 30.5 V. Their results

TABLE III. P-values for Influence of Voltage and Transfer Type in Separate Analyses

Response Variable	Voltage p-value	Transfer Type p-value
UCPC number concentration/wire feed speed	0.27	0.32
OPC 0.3–0.5 μm number concentration/wire feed speed	0.0003*	<0.0001*
OPC 0.5–0.7 μm number concentration/wire feed speed	0.0003*	<0.0001*
OPC 0.7–1.0 μm number concentration/wire feed speed	0.0016*	0.0004*
OPC 1.0–2.0 μm number concentration/wire feed speed	<0.0001*	<0.0001*
OPC 2.0–5.0 μm number concentration/wire feed speed	<0.0001*	<0.0001*
OPC >5.0 μm number concentration/wire feed speed	0.52	0.21
Total particle mass concentration/wire feed speed	0.076	0.013*
Iron mass concentration/wire feed speed	0.085	0.012*
Manganese mass concentration/wire feed speed	0.12	0.048*

Note: Response variables normalized by absolute wire feed speed.
*p-values considered significant at a level of $p < 0.05$.

may be different from results in the present study because they intentionally maintained a constant wire feed speed as they increased voltages.

Using short circuit metal transfer instead of spray transfer, when possible, may reduce welding fumes. However, short circuit is not always suitable as a welding technique because of the lack of penetration. In situations where spray arc must be used, ventilation controls and respiratory protection should be emphasized to minimize exposures to the relatively high concentrations of welding-related particles produced.

As industrial hygienists design sampling plans, metal transfer type should be taken into consideration. During basic characterization of a process, the industrial hygienist should evaluate the bulk material consumed.(25) Because higher voltage weld processes use increased wire feed speed, they burn more wire. This study found that spray arc transfer created almost five times more fumes than short circuit transfer. This information should be accounted for when forming similar exposure groups for exposure assessment. Otherwise, the variability in measured exposures could make the sampling data inconclusive.

CONCLUSIONS

Welding fume characteristics are associated with several process parameters. This research showed that higher voltage levels during welding were associated with higher concentrations of fine and ultrafine particles and metals. At a particular voltage, wire feed speed did not have a significant effect on particle concentrations over the range of speeds tested. However, the increased wire feed speeds required as voltages are increased contributed to the high fume concentrations at elevated voltages. The manganese content of particles on a percentage basis was reduced somewhat at higher voltage even though overall manganese levels generally increased with voltage.

Based on this research, minimizing voltage appears to be a promising control method. However, the requirements of the welding project may limit occasions when a lower voltage recommendation can be applied. This research also suggests that metal transfer type should be considered when establishing similar exposure groups for sampling welders during an assessment of particle exposures and for exposure controls.

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